Leading twist nuclear shadowing and hard diffraction in DIS on nuclei

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Outline

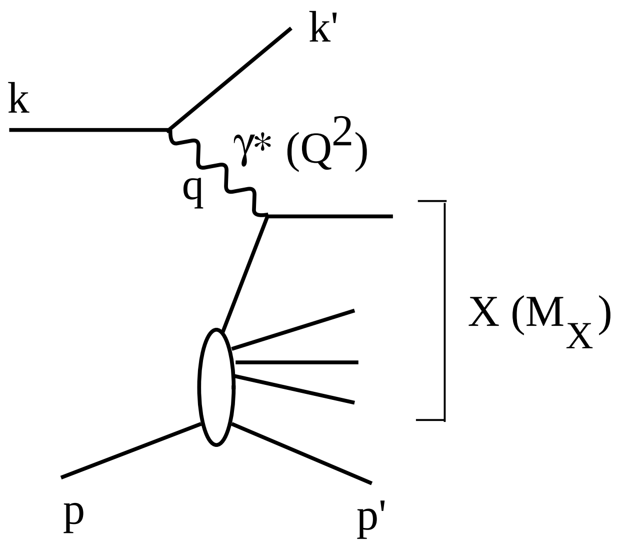
- Leading twist theory of nuclear shadowing
- Predictions for nuclear PDFs
- Predictions for nuclear diffractive PDFs
- Discussion

L. Frankfurt, VG, M. Strikman, Phys. Rev. D 71 (2005) 054001

L. Frankfurt, VG, M. Strikman, Phys. Lett. B 586 (2004) 41

VG and M. Strikman, Phys. Rev. C 75 (2007) 045208

Introduction: Inclusive diffraction in DIS



$$x_{I\!P} = \frac{M_X^2 + Q^2}{W^2 + Q^2}$$

$$\beta = \frac{Q^2}{Q^2 + M_X^2} = \frac{x}{x_{I\!P}}$$

$$t = (p' - p)^2$$

$$F_2^{D(3)}(x, Q^2, x_{I\!P}) = \int dt F_2^{D(4)}(x, Q^2, x_{I\!P}, t)$$

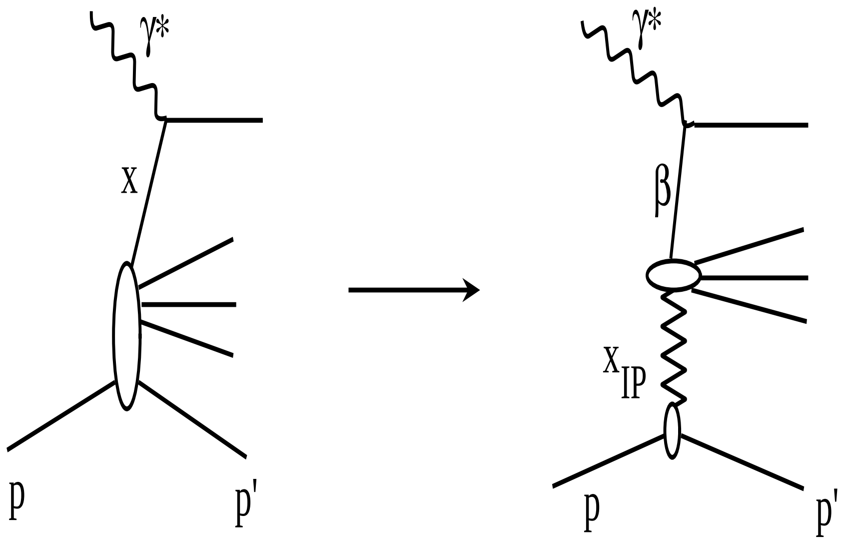
- Diffractive structure function $F_2^{D(3)}$: $\frac{d^3\sigma^{ep\to eXY}}{dx_{I\!P}dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4} F_2^{D(3)}(x, Q^2, x_{I\!P})$

- QCD factorization for diffractive DIS, universal diffractive PDFs $f_j^{D(3)}$:

$$F_2^{D(3)}(x, Q^2, x_{I\!P}) = \frac{x}{x_{I\!P}} \sum_{j=q,\bar{q},g} \int_{x/x_{I\!P}}^{1} \frac{d\beta'}{\beta'} C_j\left(\frac{x}{x_{I\!P}\beta'}, Q^2\right) f_j^{D(3)}(\beta', Q^2, x_{I\!P})$$

Introduction: Inclusive diffraction in DIS (II)

- Regge factorization assumption (supported by data)



$$f_j^{D(3)}(x, Q^2, x_{I\!P}) = f_{I\!P/p}(x_{I\!P}) f_{j/I\!P}(\beta, Q^2) + n_{I\!R} f_{I\!R/p}(x_{I\!P}) f_{j/I\!R}(\beta, Q^2)$$

– $f_{I\!P/p}$ Pomeron flux
– $f_{j/I\!P}(\beta, Q^2)$ PDF of flavor j of the Pomeron
– The subleading Reggeon contribution is negligibly small for $x_{I\!P} < 0.01$.

- The QCD analysis of diffractive data (H1 and ZEUS) determines $f_{j/I\!P}(\beta, Q_0^2)$ from global fits to (mostly) $F_2^{D(3)}$ and $F_2^{D(4)}$.

Important finding: $f_{g/I\!P}(\beta, Q_0^2) \gg f_{q/I\!P}(\beta, Q_0^2)$.

Leading twist theory of nuclear shadowing in DIS

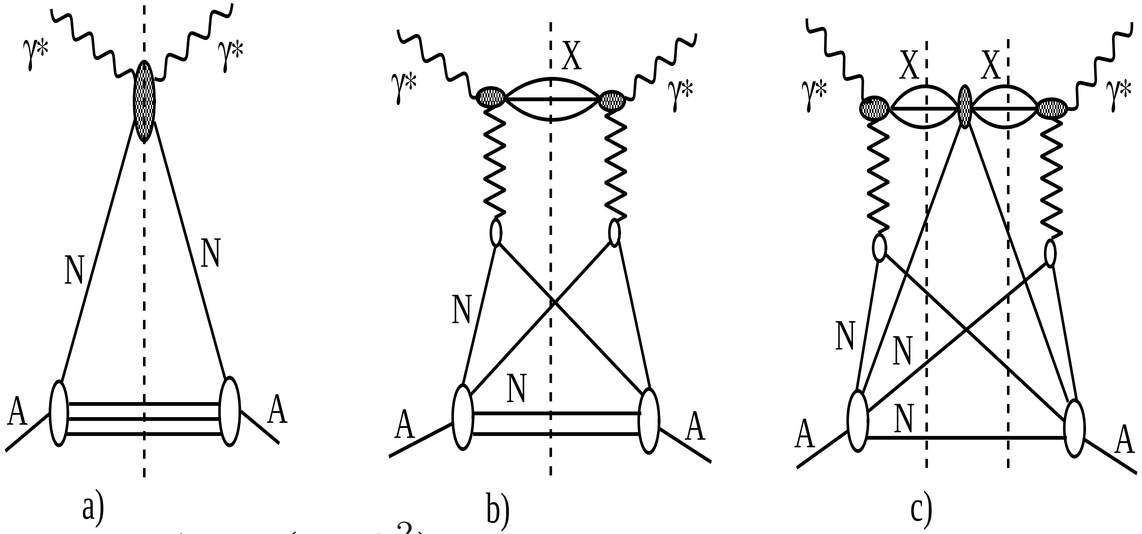
Leading twist theory of nuclear shadowing predicts **nuclear PDFs** as functions of x and b at the initial scale Q_0.

The Q^2-dependence is given by DGLAP.

The theory is based on:

- Generalization of Gribov theory to DIS and to any nucleus
  Frankfurt, Strikman '88; '99
- Factorization theorem for hard diffraction in DIS
  Collins '98
- QCD fits to HERA data on hard diffraction
  ZEUS '99; H1 '97 and '06

Step 1.

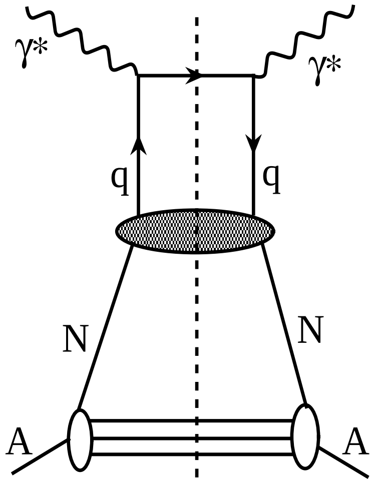


$$
\begin{aligned}
F_{2A}(x,Q^2) &= AF_{2N}(x,Q^2) \\
&- 8\pi A(A-1)\Re e\frac{(1-i\eta)^2}{1+\eta^2}\int_x^{0.1} dx_{I\!P} F_2^{D(4)}(x,Q^2,x_{I\!P},t_{\min}) \\
&\times \int d^2\vec{b}\int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \rho_A(\vec{b},z_1)\rho_A(\vec{b},z_2) e^{i(z_1-z_2)x_{I\!P}m_N} \\
&+ \ldots
\end{aligned}
$$

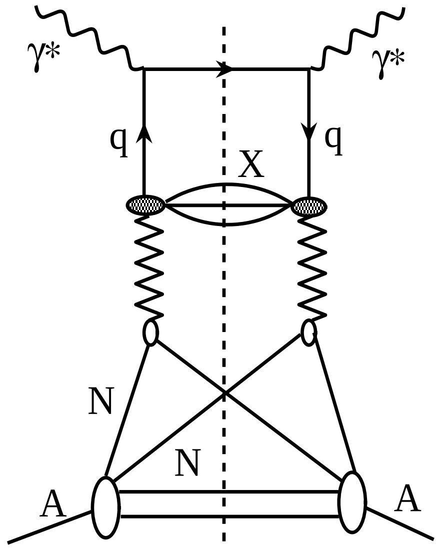
- $F_2^{D(4)}$ diffractive structure function
- ρ_A nuclear density
- $\eta = ImA/ReA$
- $e^{i(z_1-z_2)x_{I\!P}m_N}$ effect of coherence length

Step 2. QCD factorization theorems for inclusive and diffractive DIS allows us to go from structure functions to parton distributions of given flavor j:

$$
\begin{aligned}
f_{j/A}(x,Q^2) &= A f_{j/N}(x,Q^2) \\
&- 8\pi A(A-1)\Re e \frac{(1-i\eta)^2}{1+\eta^2}\int_x^{0.1} dx_{I\!P} f_{j/N}^{D(4)}(x,Q^2,x_{I\!P},t_{\min}) \\
&\times \int d^2\vec{b}\int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \rho_A(\vec{b},z_1)\rho_A(\vec{b},z_2) e^{i(z_1-z_2)x_{I\!P}m_N}
\end{aligned}
$$



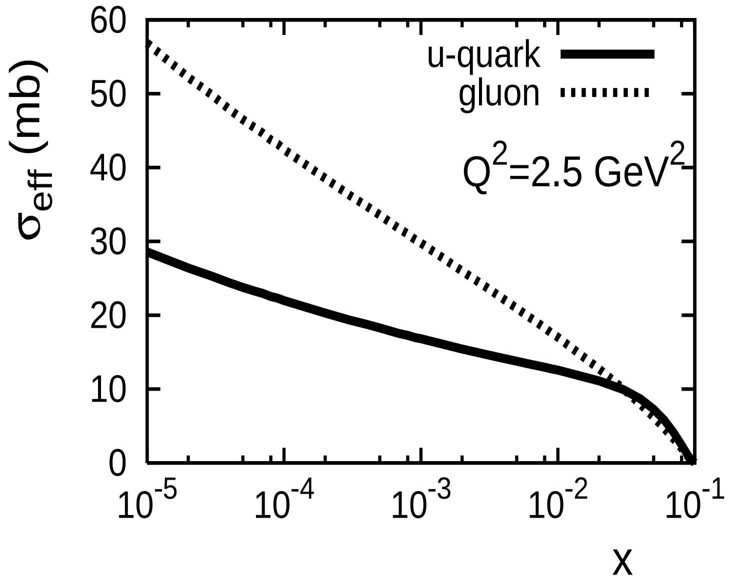
a)



b)

Step 3. The interaction with three and more nucleons is evaluated in the quasi-eikonal approximation: the produced diffractive state elastically rescatters on the target nucleons with the effective cross section $\sigma_{\rm eff}(x,Q^2)$:

$$\sigma^j_{\rm eff}(x,Q^2_0)=\frac{16\pi}{x f_{j/N}(x,Q^2_0)}\int_x^{0.1} dx_{I\!P}\,\beta f^{D(4)}_{j/N}(\beta,Q^2_0,x_{I\!P},t_{\rm min})$$

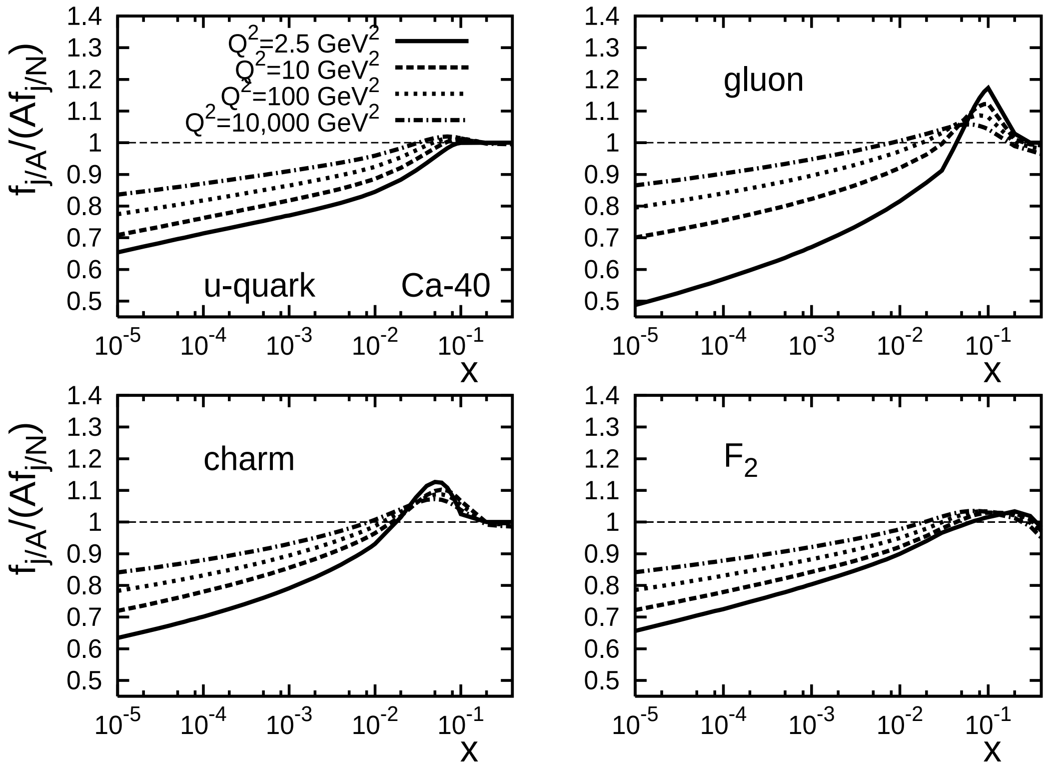


This leads to the attenuation factor $e^{-A\frac{1-i\eta}{2}\sigma^j_{\rm eff}\int_{z_1}^{z_2}dz'\rho_A(b,z')}$

$$x f_{j/A}(x,Q_0^2) = A x f_{j/N}(x,Q_0^2)$$

$$-\frac{A(A-1)}{2} 16\pi \mathcal{R}e \Bigg[\frac{(1-i\eta)^2}{1+\eta^2} \int d^2b \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \int_x^{0.1} dx_{I\!P}$$

$$\times \beta f_{j/N}^{D(4)}(\beta, Q_0^2, x_{I\!P}, t_{\min}) \rho_A(b,z_1) \rho_A(b,z_2) e^{i x_{I\!P} m_N (z_1-z_2)} e^{-A \frac{1-i\eta}{2} \sigma_{\rm eff}^j \int_{z_1}^{z_2} dz' \rho_A(b,z')} \Bigg]$$

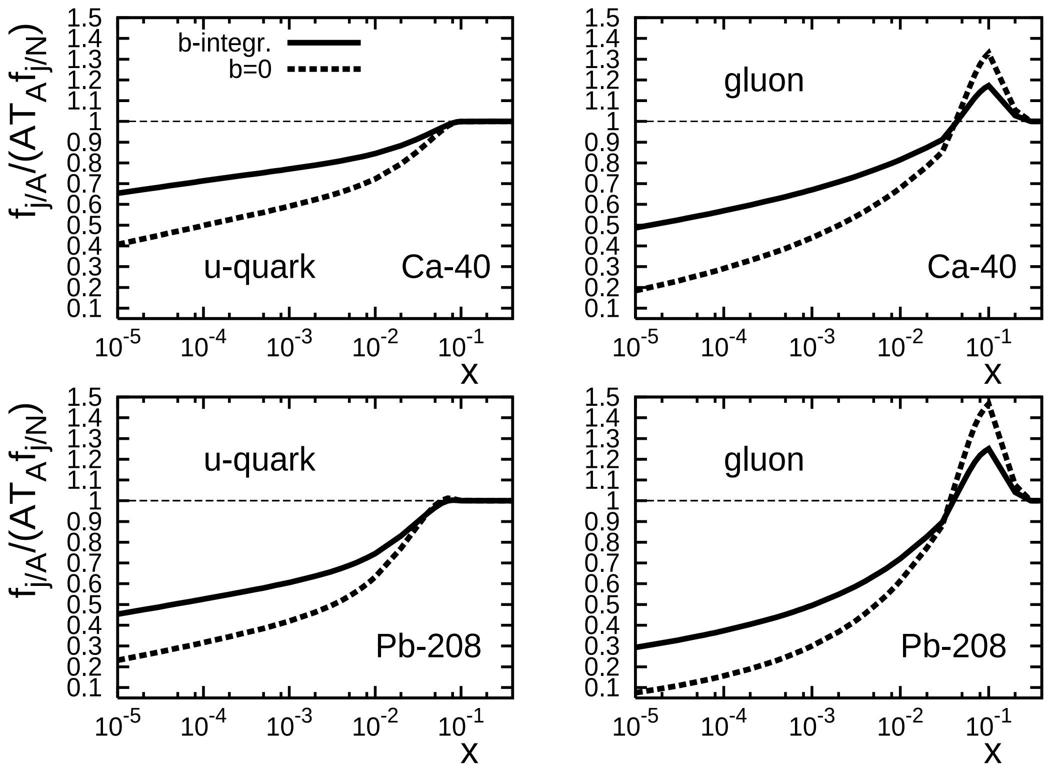


Impact parameter dependent nPDFs

$$x f_{j/A}(x,\mathbf{b},Q_0^2) = A T_A(\mathbf{b}) x f_{j/N}(x,Q_0^2)$$

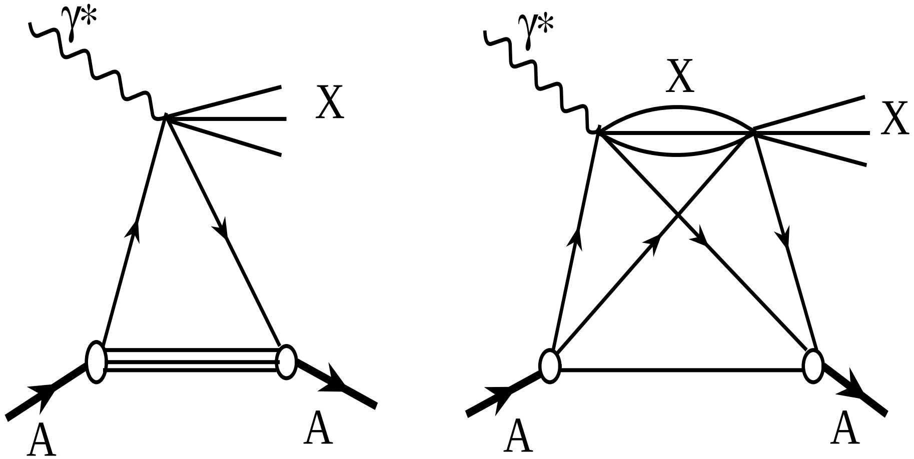
$$-\frac{A(A-1)}{2}16\pi \mathcal{R}e\left[\frac{(1-i\eta)^2}{1+\eta^2}\int_{-\infty}^{\infty}dz_1\int_{z_1}^{\infty}dz_2\int_{x}^{0.1}dx_{I\!P}\right.$$

$$\left.\times\beta f_{j/N}^{D(4)}(\beta,Q_0^2,x_{I\!P},t_{\min})\rho_A(\mathbf{b},z_1)\rho_A(\mathbf{b},z_2)e^{ix_{I\!P}m_N(z_1-z_2)}e^{-A\frac{1-i\eta}{2}\sigma_{\rm eff}^j\int_{z_1}^{z_2}dz'\rho_A(b,z')}\right]$$



Nuclear diffractive PDFs

LT theory of nuclear shadowing can also be used to calculate nuclear diffractive PDFs which are measured in coherent (inclusive) diffraction in DIS on nuclei

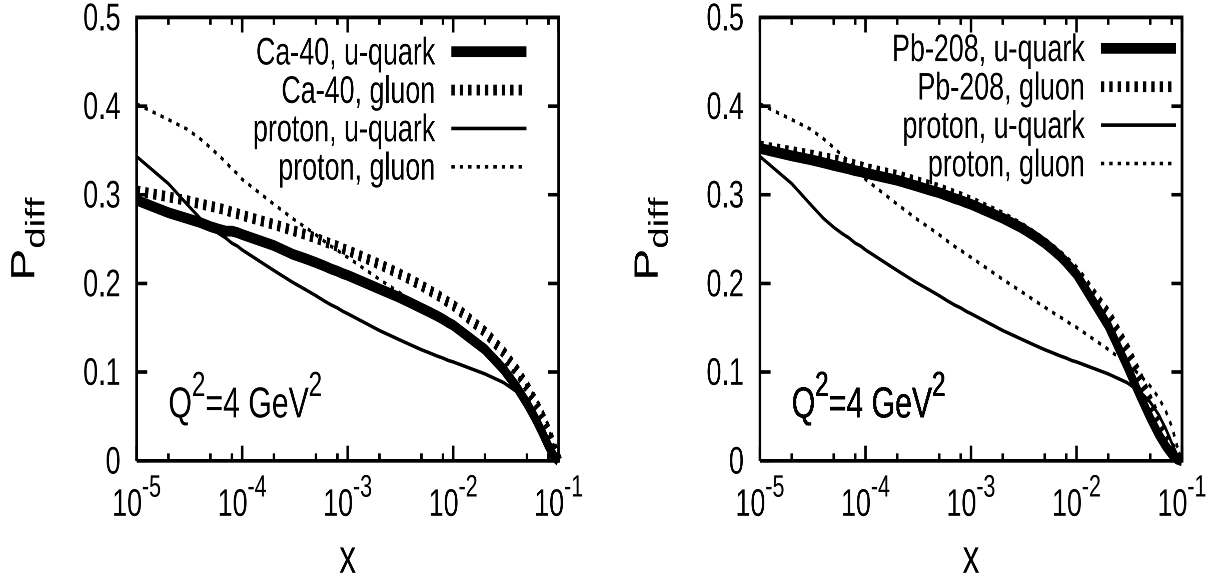


$$x f_{j/A}^{D(3)}(x, Q_0^2, x_{I\!P}) = 4\pi A^2 \beta f_{j/N}^{D(4)}(x, Q_0^2, x_{I\!P}, t_{\min}) \int d^2 b \times \left| \int_{-\infty}^{\infty} dz\, e^{i x_{I\!P} m_N z} e^{-\sigma_{\rm eff}^j(x,Q_0^2)/2 \int_z^{\infty} dz' \rho_A(b,z')} \rho_A(b,z) \right|^2$$

The Q^2 evolution is by DGLAP.

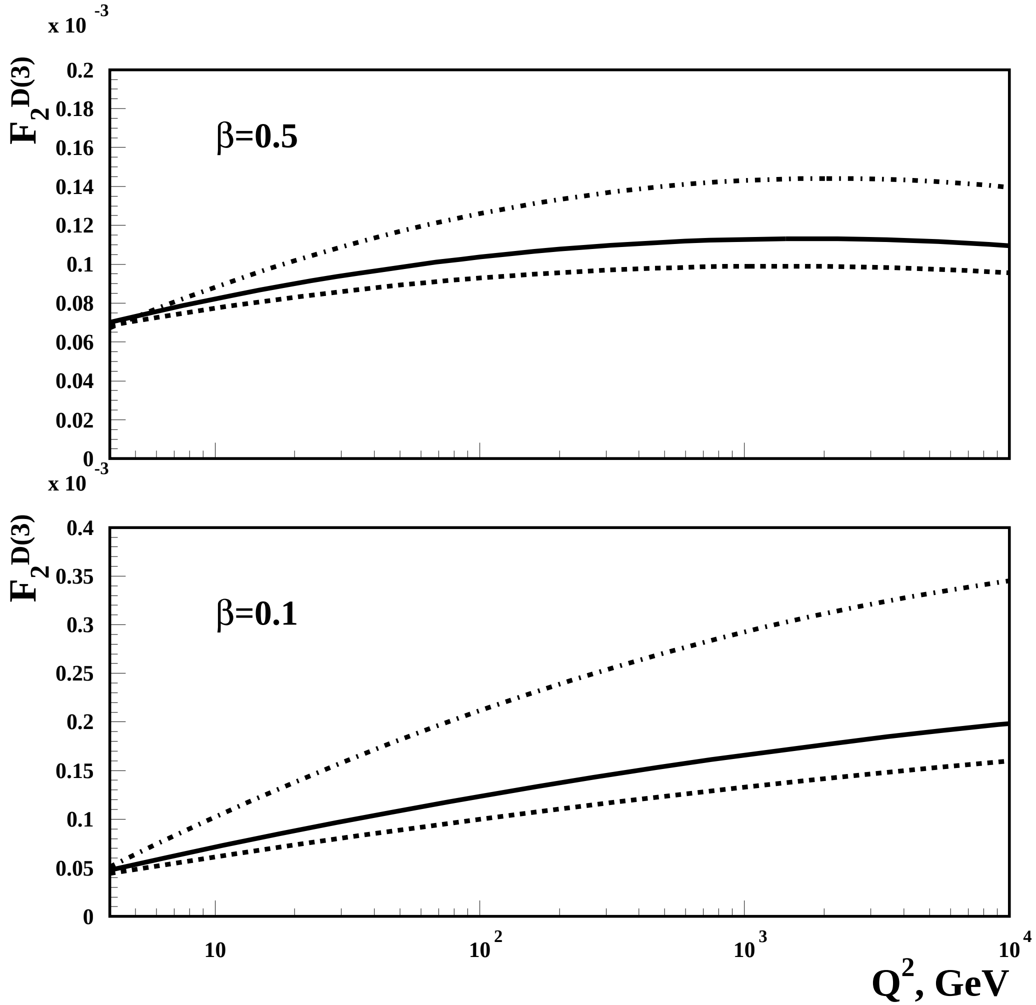
Probability of diffraction

$$P_{\rm diff}^j = \frac{\int_x^{0.1} dx_{I\!P}\, x f_j^{D(3)}(x, Q_0^2, x_{I\!P})}{x f_j(x, Q_0^2)} \le \frac{1}{2}$$



- Surprisingly, we do not observe nuclear enhancement of $P_{\rm diff}^j$ on nuclei.
- This is the effect of the (gray) nuclear surface; at central b, $P_{\rm diff}^j \approx 1/2$.
- Does diffraction help to study the regime of high parton densities/saturation?

Predictions for $F_2^{D(3)}$



$x_{I\!P} = 0.001$

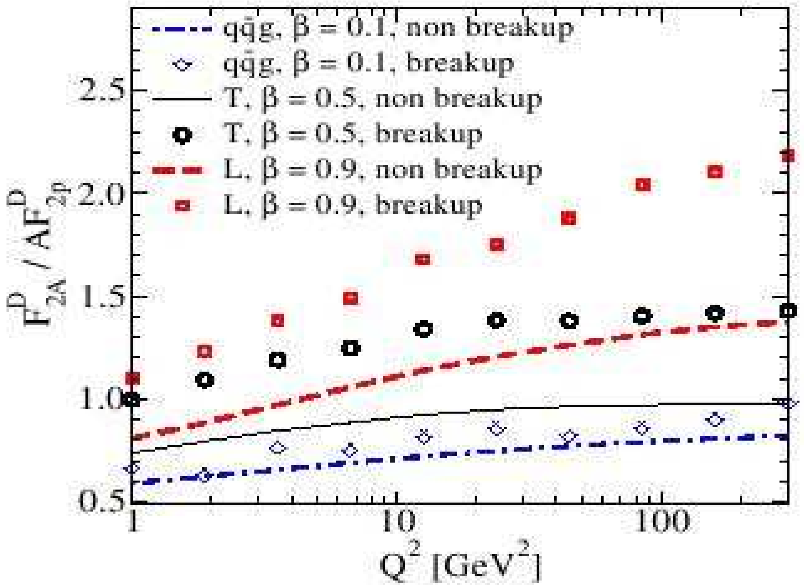
Solid – ^{40}Ca
Dotted – ^{208}Pb
Dot-dashed – proton

Arbitrary normalization!

L. Frankfurt, VG, M. Strikman, Phys. Lett. B 586 (2004) 41

Discussion 1

Need to calculate $F_{2A}^{D(3)}/[AF_{2N}^{D(3)}]$ and to compare to Kowalski, Lappi, Marquet and Venugopalan, arXiv: 0805.4071 [hep-ph].



However, $F_{2A}^{D(3)}/[AF_{2N}^{D(3)}]$ is not the best quantity since:

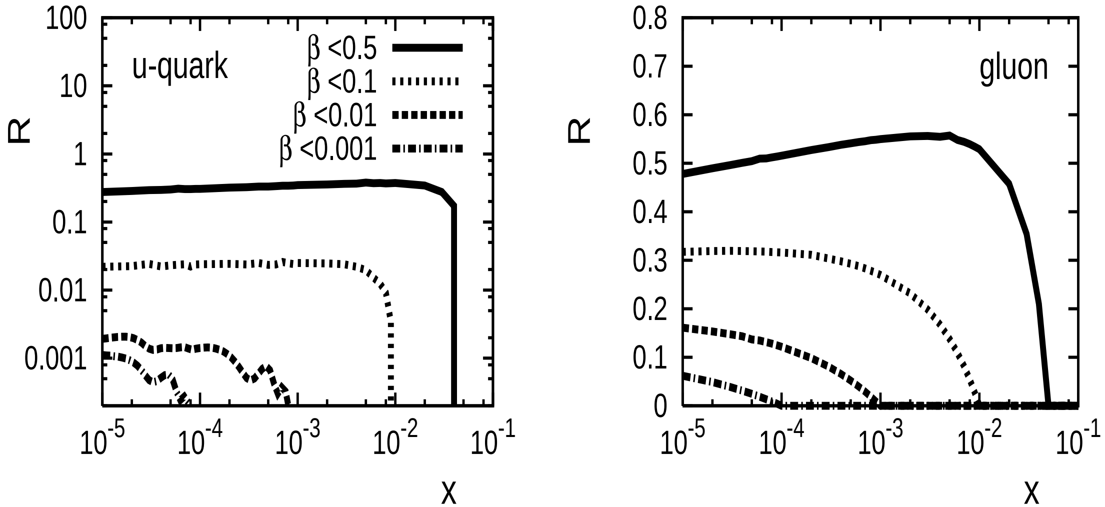
- $F_{2A}^{D(3)}/[AF_{2N}^{D(3)}] \propto A^{1/3}$ in the Color Transparency limit
- $F_{2A}^{D(3)}/[AF_{2N}^{D(3)}] \propto A^{-1/3}$ in the Black Disk limit

Discussion 2: Why do we not observe nuclear enhancement of $P^j_{\rm diff}$?

- Non-linear/saturation effects are expected for $\beta = x/x_{I\!P} = Q^2/(Q^2+M_X^2) \ll 1$ (for large diffractive masses $M_X^2 \gg Q^2$).
  E.g. recall derivation of the Black Disk limit, L. Frankfurt *et al.*, PRL 87 (2001) 054503

- However, in our approach, the small-β region plays an insignificant role.

$$R(\beta_{\max}, x) \equiv \frac{\int_x^{0.1} dx_{I\!P} \beta f^{D(3)}_{j/N}(\beta, Q_0^2, x_{I\!P}) \Theta(\beta_{\max} - \beta)}{\int_x^{0.1} dx_{I\!P} \beta f^{D(3)}_{j/N}(\beta, Q_0^2, x_{I\!P})}$$



Summary

- The leading twist theory of nuclear shadowing makes definite predictions for nuclear diffractive PDFs and diffractive structure functions for coherent diffraction.

- One can study the dependence on x, Q^2, $x_{I\!P}$ and A.

- The saturation limit is not reached due to the diffuse edge of nuclei and due to the insignificant role of the small-β (large-M_X^2) region.